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Block-Structured Solution of Three-Dimensional Transonic Flows Using Parallel Processing

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The main objective of the program has been to implement and test the three-dimensional, block-structured Euler solver on computers with multiple processors. The developed scheme involves the partitioning of a large aerodynamics problem into several smaller problems where each represents a particular flow region. Each of these problems are Intel-IPSC computer with sixteen processors and IBM 3090 computer with four processors. In the case of IPSC, the memory is distributed between sixteen processors (4.5 megabytes each). In the case of IBM 3090, all four processors share the same large memory. Several test cases have been run on these computers and basic considerations for analyzing large problems on parallel computers have been investigated.

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for the period of
June 1, 1987 - May 31, 1989

PURDUE UNIVERSITY

School of Engineering
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by

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TABLE OF CONTENTS

1. Objectives

The main objective of the research program has been to develop and implement a three-dimensional, block-structured (zonal) solution scheme for Euler equations on computers with multiple processors. The methodology is aimed at developing computational techniques for solving three-dimensional, transonic flow problems around complex geometries. For solving problems such as transonic flow around an aircraft, one expects to employ many computers for the solution of a single problem. The developed scheme involves the partitioning of a large aerodynamics problem into several smaller problems where each sub-problem is defined for a particular flow region. Each of these problems are then solved on individual processors. The boundary condition between the neighboring flow regions are communicated between these processes. This work has been the continuation of a development over the years for generating grids for complex geometries and solving large problems for such geometries by using a zonal approach and finally studying the appropriate computer architectures for solving such problems. The main publications describing the research work are:

1. Ecer, A., Spyropoulos, J.T., and Maul, J.D., "A Three-Dimensional, Block-Structured Finite Element Grid Generation Scheme," AIAA Journal, Vol. 23, Oct. 1985, pp. 1483-1490.
2. Ecer, A. and Spyropoulos, J.T., "Block-Structured Solution Scheme for Analyzing Three-Dimensional Transonic Potential Flows," AIAA Journal, Vol. 25, Oct. 1987, pp. 1292-1300.
3. Ecer, A., Spyropoulos, J.T. and Rubek, V., "Block-Structured Solution of Euler Equations for Transonic Flows," AIAA Journal, Vol. 25, Dec. 1987, pp. 1570-1576.

4. Ecer, A., Spyropoulus, J.T., Sims, M., Parallel Processing Techniques for the solution of Euler Equations, AIAA Paper 88-0620. AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1988.

2. Description of the Method of Solution

The method of solution is documented in several papers in detail. Here a short summary of the methodology is provided:

a) Block-Structured Grid Generation Scheme (ref. 1).

Flow field around a complex geometry is represented by an assembly of flow regions. Each region corresponds to a simpler geometry (a block) which can be defined easily. These blocks are attached to each other for describing the complex flow field. The block-structure can be irregular i.e. blocks can be attached to each other in an unstructured fashion. The procedure keeps track of the block-structure at all times. In designing a computational grid, one specifies the grid required for each block. The blocks are automatically connected to each other. Besides representing complex geometries, the blocks are used to model specific flow structures. For example, a block is placed to include the flow region where a shock occurs. One can then specify the required grid refinement around the shock and this grid is automatically connected to the neighboring flow regions. This methodology is also useful when one starts with a computational grid and modifies it locally after observing the accuracy of the obtained results. Any local grid modifications is propagated to the neighboring blocks automatically.

b) Block-Structure Solution Schemes (ref 2,3).

After the computational grid is generated in terms of a series of blocks, the solution of Euler equation is defined in terms of the solution of the equations for each of the blocks with interface boundary conditions between the neighboring blocks. The steady-Euler equations are solved by using a relaxation scheme where the velocity vector is decomposed by using a Clebsch transformation as follows:

$$\underline{u} = \underline{\nabla}\phi + S\underline{\nabla}\eta$$

where S is the enhopy, ϕ and η are Lagrange multipliers. The Euler equations are written in terms of these variables as follows:

$$\underline{\nabla}(\rho\underline{\nabla}\phi) = - \underline{\nabla}(\rho S\underline{\nabla}\eta)$$

$$\underline{\nabla}.(\rho u S) = 0$$

$$\rho\underline{u} \; . \; \underline{\nabla}\eta = - p/R$$

where ρ is the density, ρ is the pressure and R is the gas constant. For blocks with out rotationbity (Constant entropy) one needs to solve only the first equation. The boundary conditions between the neighboring blocks requires the continuity of ϕ, S and η. For potential equation, only the continuity of ϕ is required. The solution scheme require iterative solution of these equations in each of the blocks together with the iteration of the boundary conditions between the neighboring blocks. An efficient methodology for iterating the boundary conditions for ϕ, S and η have been developed.

c) Parallel Processing for Block-Structured Solution of Euler Equations (ref.4):

The developed methodology is well suited for parallel processing. For a given computer with many processors, the blocks are distributed among the processors. The information exchange between the neighboring processors involve only the exchange of boundary conditions which is a relatively small set of data. In terms of parallel processing, two types of computers were tested. For a computer with distributed memory (Intel-IPSC) each of the blocks is stored on an individual computer with its own memory. For a computer with shared memory (IBM 3090), the memory is shared by several processors. In the first case, the numbers of processors and the blocks are matched. In the second case, the number of blocks is much larger than the number of processors.

The objective of this part of the study was to investigate the applicability of parallel processing for solving large aerodynamics problems. The methodology is quite general and numerical results have been obtained for several practical problems in a parallel environment. The completed work resents one of the few applications of relaxation schemes in a parallel computing environment.

3. Summary of the Research:

The research work on the block-structured solution of Euler equations with parallel processing progressed along four main areas:

A. Implementation of the Block-Structured Solution Scheme on a Intel hypercube with distributed memory and sixteen processors.

B. Implementation of the Block-Structured Solution Scheme on a IBM 3090 computer with shared memory and four processors.

C. Configuration of Grid Generation Studies.

A. Implementation of the Block-Structured Solution Scheme on a Intel Hypercube.

This activity involved the solution of aerodynamics problems on a computer with many processors each with its own individual memory (distributed memory). The example in figure 1 shows the sixteen block model of a wing body problem. In this case, each block is stored on an separate computer. Grids are generated on a block-by-block bases and the solution is obtained for each block. The only exchange of information between the neighboring blocks is the

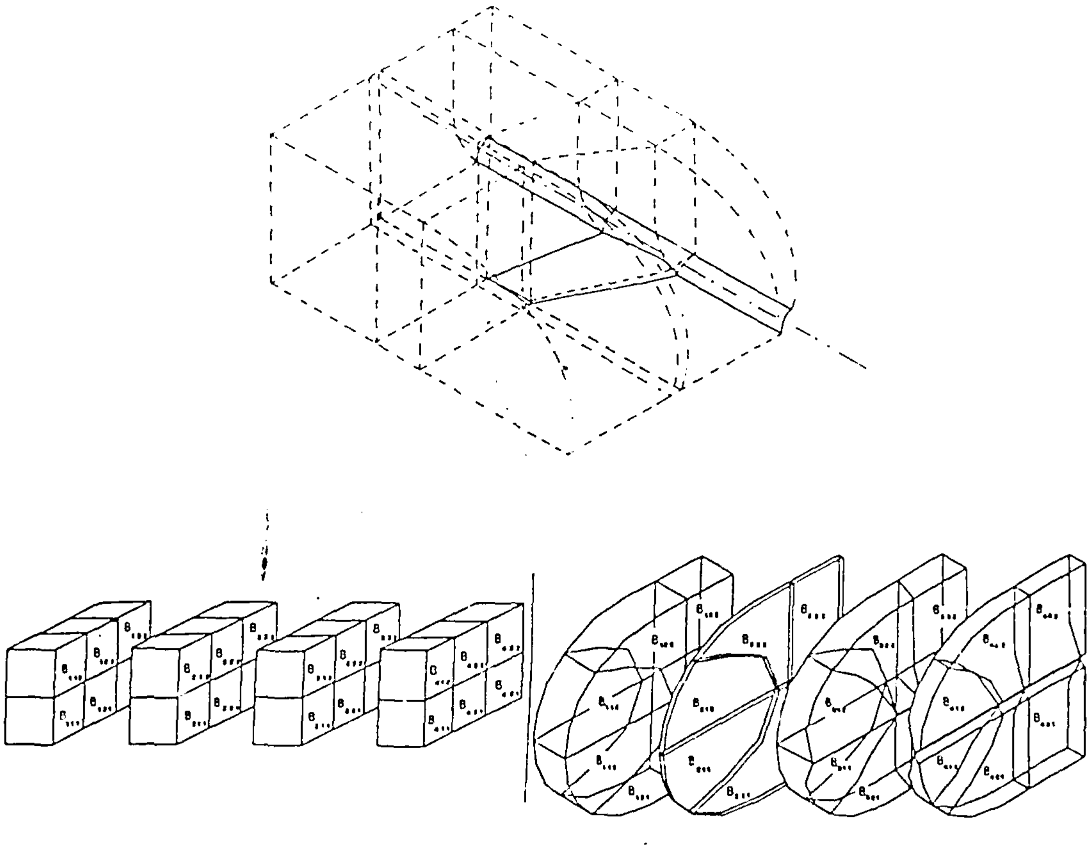


FIG. 1a. Block-Structure for the Wing-Body Problem.

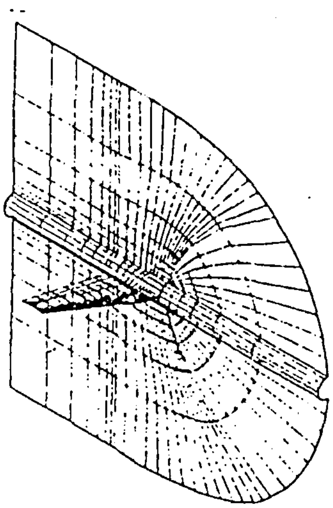


FIG. 1b. Grid Distribution over the Wing-Body.

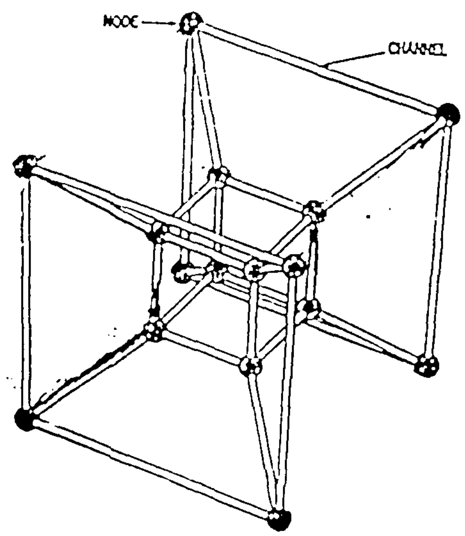


FIG. 1c. Node configuration on INTEL Computer for the sixteen block model

boundary conditions. This application is one of the first implementations of a three-dimensional CFD code on a Intel Hypercube computer.

The following papers were written describing this work:

1. Ecer, A., Spyropoulus, J.T., Sims, M., Parallel Processing Techniques for the solution of Euler Equations, AIAA Paper 88-0620. AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 11-14, 1988.
2. Ecer, A., Spyropoulus, J.T., Block Structured Solution of Euler and Naiver-Stokes Equations, 2nd Int. Symp. on Domain Compositions Methods, USC, Los Angeles, January 14-16, 1988. (invited paper)
3. Ecer, A., Spyropoulus, J.T., and Sims, M., The Solution of Euler Equations on a Hypercube, 3rd Conf. on Hypercube Concurrent Computers and App., Caltech, Pasadena, January 19-20, 1988.
4. Ecer. A. and Akay, H.U., A Block-Structured Finite Element Solution of Viscous Internal Flows, Int. Conf. on Comp. Meth. in Flow Analysis, September 4-8, 1988, Okayoma, Japan. (invited paper)
5. Ecer, A., & Spyropoulos, J.T., "Parallel Processing Schemes for the Block-Structured Solution of Transonic Flows," Society Computer Simulation Summer Conference, Ontario, Canada, July 23-29, 1987.

B. Implementation of the Block-Structured Solution Scheme on IBM-3090 Computer.

In this case, the same problem was implemented on a computer where four processors share the same large memory as shown in figure 2. Many blocks are solved on each of the processors where one can address several gigabytes of memory in an efficient manner by using the developed scheme. Presently a 12 processor version of this application is attempted. We have been collaborating with IBM research center in Kingston on this activity.

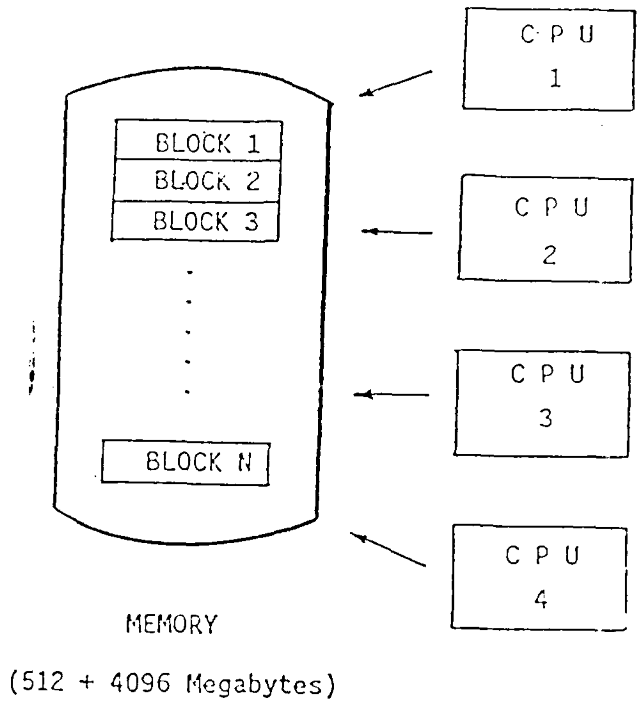


Fig. 2. Block-structured solution scheme on an IBM 3090-E computer.

The implementation of the scheme on parallel processors for solving large problems was investigated by using the developed capability. Numerical results were obtained for a nacelle and a wing-nacelle configuration which involve over 150 blocks as shown in figure 3. Presently a F-16 geometry aircraft (over 500,000 grid points) is under investigation as shown in figure 4.

. The following papers was prepared describing this activity:

1. Chang, S.M., Ecer, A. and Spyropoulos, J.T., "The Use of IBM Parallel FORTRAN and Multitasking facility with a Domain Decomposition Approach for the Euler Equations," IBM Symposium on Parallel Processing Poughkeepsie, New York, Oct. 19-21, 1988.
2. Ecer, A., Spyropoulos, J.T. & Chang, S.M. "Parallel Processing Schemes for the Block-Structured Solution of Transonic Flows II," Society of Computer Simulation Summer Conference, Seattle, Washington, July 25-28, 1988.
3. Chang, S.M., Ecer, A. and Spyropoulos, J.T., "Parallel Processing Techniques of the Euler Equations on the IBM 3090 VF Computer," The Second International Conference on Vector & Parallel Computing Issues in Applied Research and Development, Tromso, Norway, June 6-10, 1988.
4. Chang, S.M., Ecer, A. and Spyropoulos, J.T., "Parallel Processing Techniques on the IBM 3090VF Computer System," 7th International Conference on Finite Element Methods in Flow Problems, Huntsville, Alabama, Apr. 3-7, 1989.
5. Spyropoulos, J.T., Ecer, A. Rout, R.K., and Badesha, S.S., "Block-Structured Solution of Three-Dimensional Transonic Flowfields for Wing/Pylon/Nacelle configurations," AIAA Paper 89-2940, 25th Joint Propulsion Conference, Monterey, California, July 10-14, 1989.

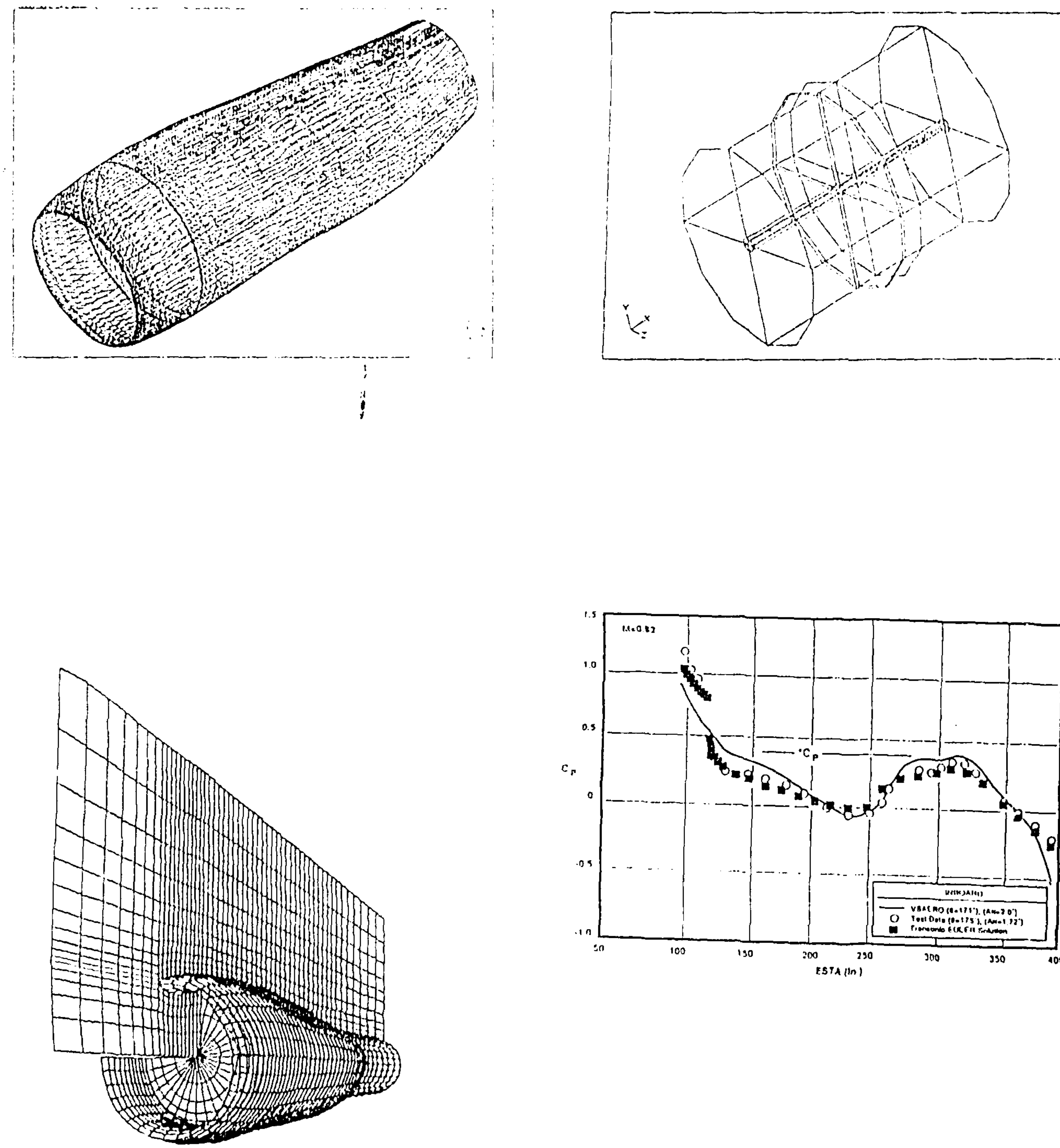
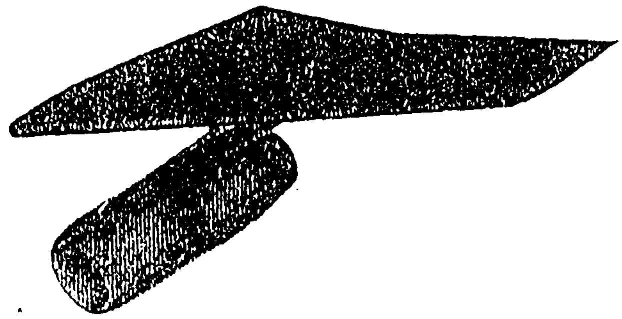
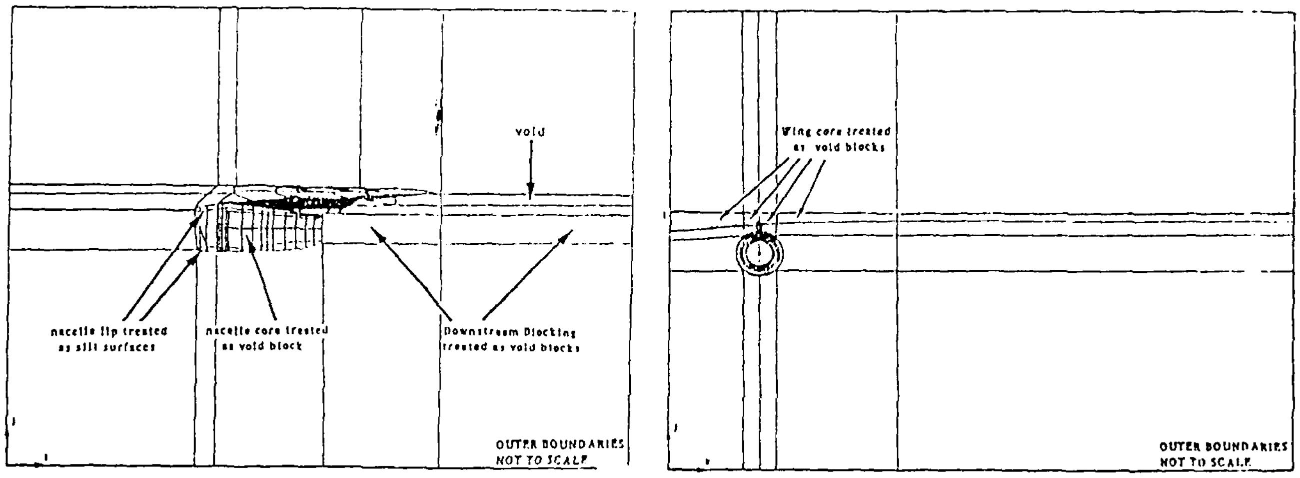


Figure 3a. Block-Structured Solution of Isoleted Nacelle Problem.





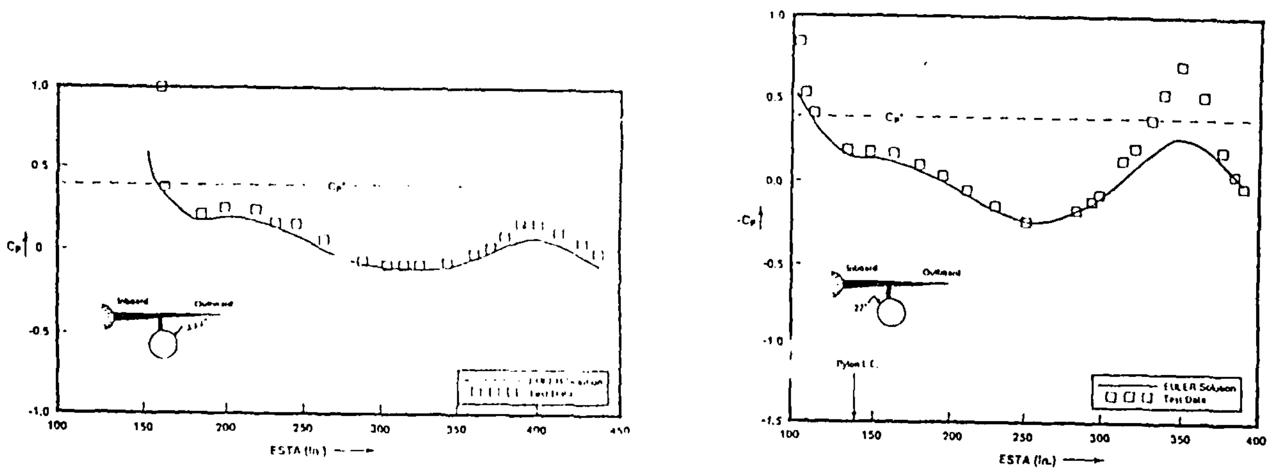
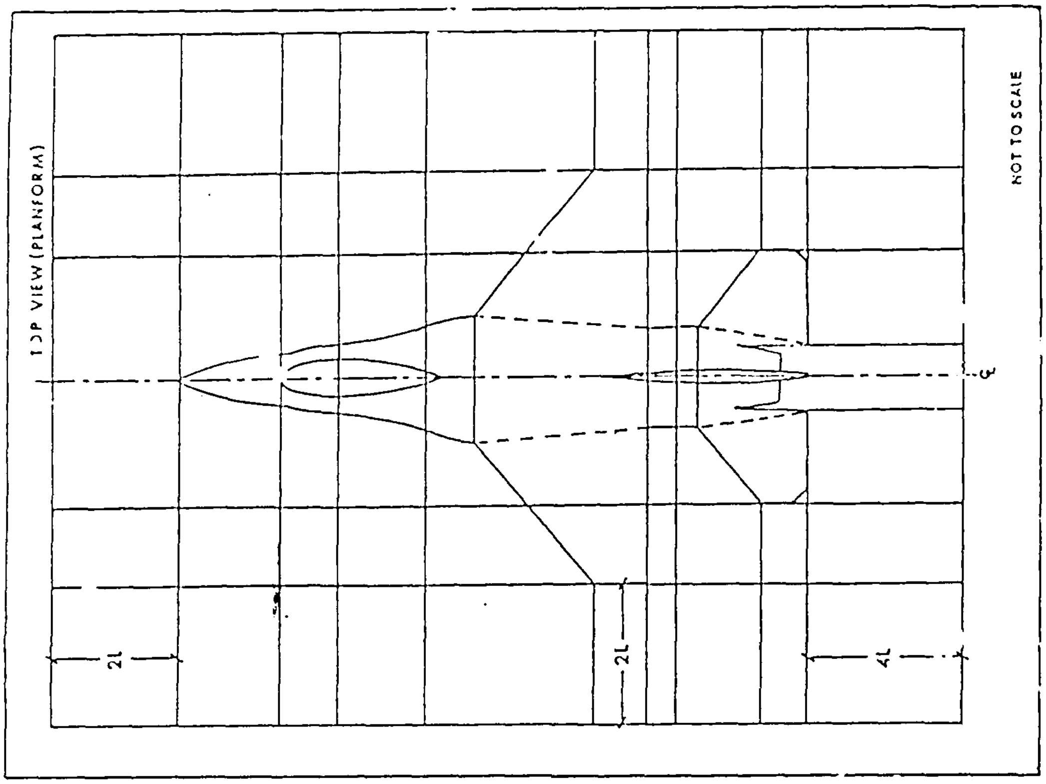


Figure 3b. Block-Structured Solution of Installed Nacelle Problem.



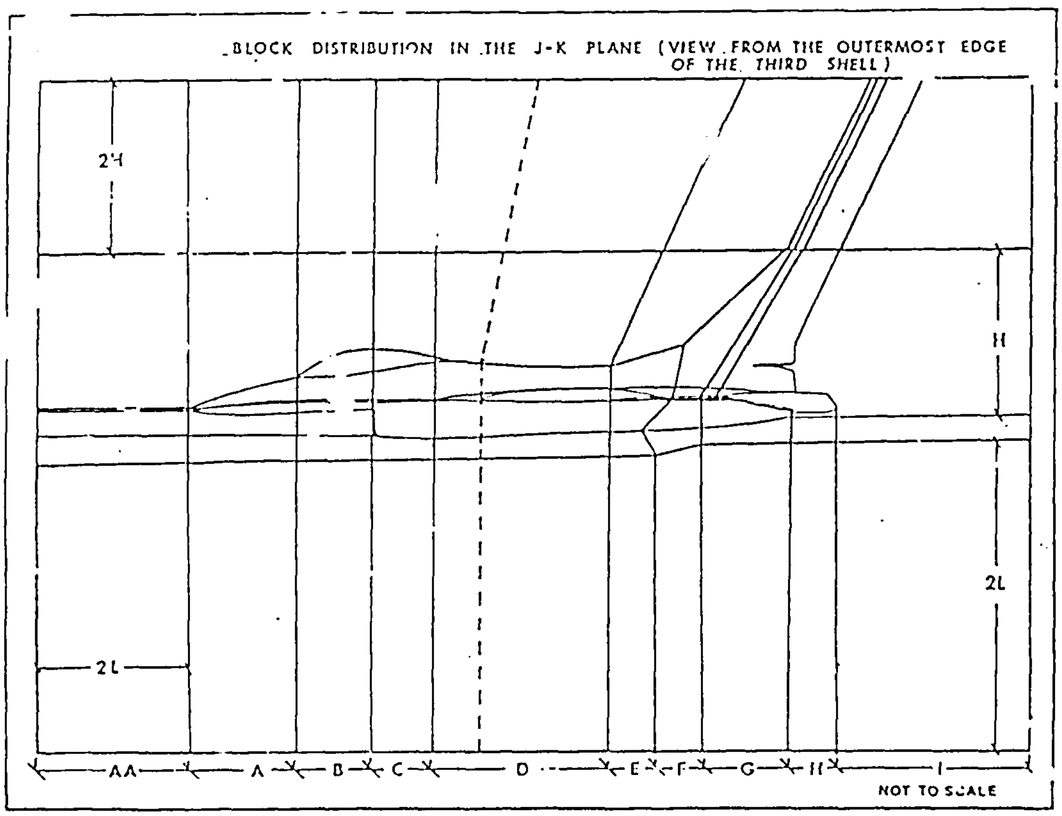


Figure 4a. Block-Structure for the F-16 aircraft

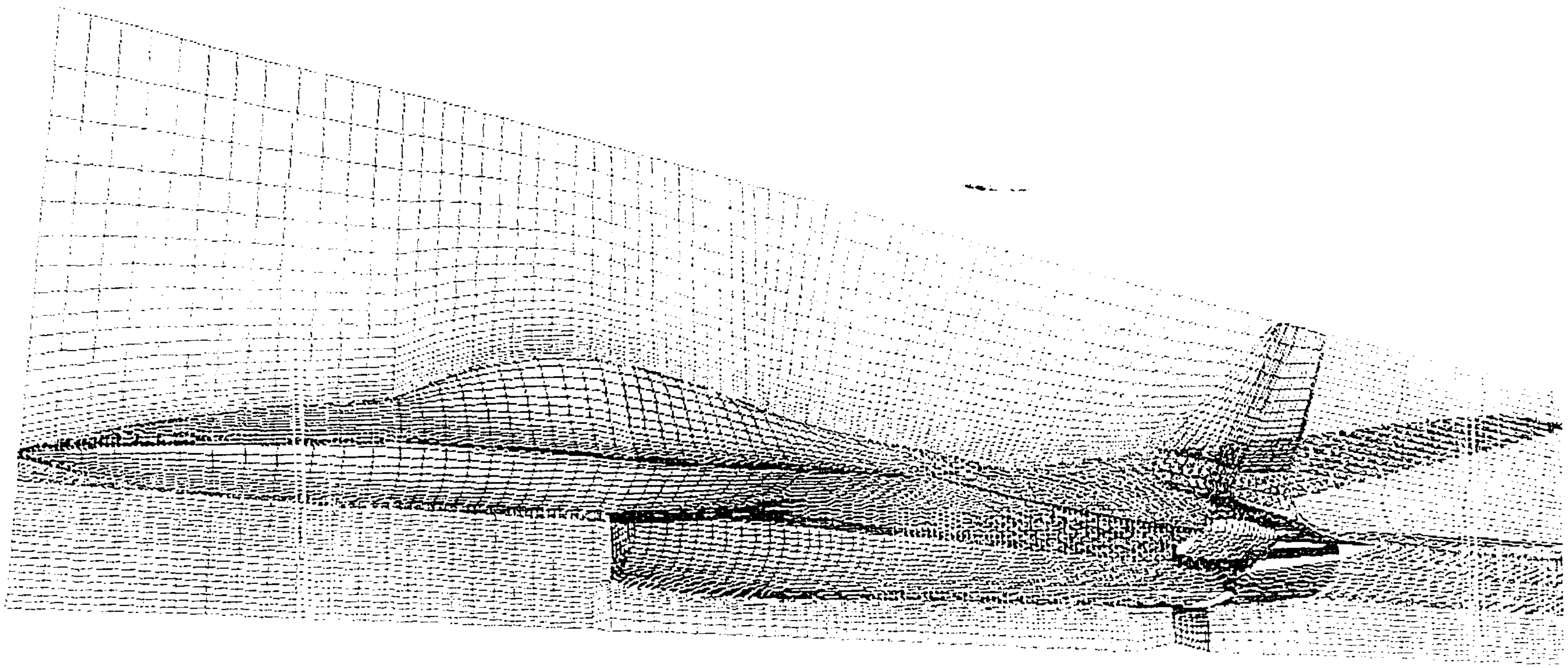


Figure 4b. Block-Structured Grid for the F-16 Aircraft

C. Grid Generation Studies.

The continuation of the grid generation studies were basically focused on testing the accuracy and efficiency of the scheme for complex geometries.

The following papers were written describing this activity:

1. Ecer, A., Spyropoulos, J.T., Application of a Three-Dimensional Finite Element Grid Equation Scheme for Analyzing Transonic Flow Around an Aircraft, Conf. on Automated mesh Generation and Adaptation, Grenoble, France, Oct. 1987. (invited)
2. Ecer, A., Spyropoulos, J.T. and Bulbul E., Application of a Three-Dimensional Finite Element Grid Generation Scheme for F-16 Aircraft Configuration, 2nd Int. Conf. on Num Grid. Generation in Comp. Fluid Dynamics, Miami Beach, Dec. 5-8, 1988.
3. Ecer, A., Akay, H.U. and Spyropoulos, J.T., "Applications of a Three-Dimensional Finite Element Grid Generation Scheme to Flow Problems," 5th International Conference on Numerical Methods in Laminar and Turbulent Flows, Montreal, Canada, July 6-10, 1987.

4. Conclusions

The main objective of the research has been the development of methodology for solving large transonic flow problems with complex geometries. One can develop a basic computational procedure for solving a particular flow problem around a two-dimensional simple geometry (eq. an airfoil). However, it is not always easily possible to perject the applicability of this procedure for solving, complex, three-dimensional flow problems. We have been using finite element methods for solving CFD problems basically due to their flexibility in modeling complex geometries (unstructured grids). However, our experience with large problems indicated that it is very difficult to treat large problems as a single problem. Even if one can generate "a grid" for a complex geometry it requires several iterations to ensure that this is "an acceptable grid" in terms of providing disired accuracy with available computational resources. In terms of solving Euler equations, we have also reduced the problem to the solution of potential or non-isentropic potential equation for the majority of the flow field with the solution of the Euler equations only at certain critical regions. In terms of accuracy of the solutions in isentropic flow regions, the solution of potential equations are quite satisfactory with coarser grids then the ones used for Euler equations docummented in the literature. In the developed block-structured solution scheme, one can define which specific regions (blocks) will be analyzed by using the Euler equations and provide desired grid accuracy in these regions. The block-structure solution schemes become even more powerful when the solution of Naiver-Stokes equations are sought which requires considerably refined grids.

The parallel processing of the Euler equations proved to be a natural extension of the developed technology. While the computational speed and size of computers is expected to increase in coming years, one can easily expect grids with 10^8 - 10^9 grid points to be still quite expensive on a single processor. There is agreement among many researchers that parallel processing may be the most feasible way for solving such large problems. It is important to note that if one is going to solve a large problem on parallel computers one should consider the methodology which will work efficiently on such machines. As can be seen from the present research, the grid generation, the solution scheme and the computer implementation must be considered as a single problem. The conversion of an existing computational procedure and a computer code to a parallel machine does not always produce impressive results. Some of the current issues in CFD such as adaptive grids, efficiency and accuracy of computational schemes has to be studied in conjuction their with application to parallel computers. For example, many computational schemes which have been developed for structured grids are being revised in terms of their application to unstructured grids. One expects a similar activity in the future, in terms of implementing different schemes for parallel computers. Instead, it seems more logical to develop computational schemes with the objective that they will work on parallel computers. The completed work provides such an example where a complete methodology is developed for solving CFD problems, in particular transonic flows, in a parallel computing enviroment.